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Vorwort

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Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Dieter Prätzel-Wolters

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

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INVARIANT INPUT LOADS FOR FULL VEHICLE MULTIBODY SYSTEM SIMULATION

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Abstract. *Input loads are essential for the numerical simulation of vehicle multibody system (MBS)- models. Such load data is called invariant, if it is independent of the specific system under consideration. A digital road profile, e.g., can be used to excite MBS models of different vehicle variants. However, quantities efficiently obtained by measurement such as wheel forces are typically not invariant in this sense. This leads to the general task to derive invariant loads on the basis of measurable, but system-dependent quantities. We present an approach to derive input data for full-vehicle simulation that can be used to simulate different variants of a vehicle MBS model. An important ingredient of this input data is a virtual road profile computed by optimal control methods.*

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1 INTRODUCTION

The numerical simulation of full-vehicle multibody-system(MBS)- models plays an important role in the development and prototyping process. In contrast to an experimental measurement, a virtual simulation is less extensive and time-consuming. Different vehicle variants can be simulated and analyzed very effectively. Naturally, this includes the simulation of new prototypes, which may only exist as numerical models. Important ingredients of a full-vehicle simulation are input loads that properly describe a road or a test-track. Such load data is called *invariant*, if it is independent of the specific vehicle under consideration. This independence-property is essential if the input loads shall be used to simulate different vehicle variants.

An natural choice of input data for full-vehicle simulation is a digital road profile; obviously, this is an invariant input data. However, the approach has two major drawbacks: First of all, in order to obtain such a digital road profile, the (public) road or the test-track has to be measured, saved and processed to be usable in a computer simulation, this requires very complex and elaborated sensor techniques, it is very time-consuming and costly. Second, a good tire model is needed that approximated the typically nonlinear behaviour of the real tire in a suitable way. Such tire models are very difficult to obtain, either they are only appropriate for specific simulations scenarios or their simulation takes a computation time that makes it impossible to simulate more than a few seconds. Thus, these models are not appropriate for a full-vehicle simulation, for which simulation times of several minutes up to hours are typical. A further approach to generate input loads uses measured wheel forces and torques. This approach requires a test vehicle that drives over a road or a test-track. Section forces and torques are measured at the vehicle's rim during that drive. This can be realized in a comparably cheap and efficient way. In a MBS simulation, these measured signals can be applied directly to the rims of a vehicle MBS model; no tire model is necessary. However, the wheel forces and torques are *not* invariant, they highly depend on the vehicle that was used for the measurement and, thus, they can only be applied to a model of that test vehicle. Therefore, to overcome this lack of invariance, the task arises to derive invariant input data based on measured quantities and a MBS model of the test vehicle.

In this contribution we propose and analyze an approach to solve this task. We introduce a specific tire surrogate model and, based on this model and on measured section quantities, a virtual road profile is derived. This virtual road profile together with the tire surrogate model can be used to simulate other vehicles models that vary within a specific class w.r.t to the used test-vehicle. The term 'virtual' is crucial and shall be explained later.

The remaining part of this paper is organized as follows: In section 2, we sketch the basic idea of our approach. In particular, the optimal control problem whose solution yields the virtual road profile is formulated. Section 3 presents a case study highlighting the general approach and showing the invariance-properties of the proposed input data. We finish with some concluding remarks.

2 GENERAL APPROACH

Basically our approach can be described as follows: Suppose that we have a MBS model of the test vehicle without tire models. The MBS model is simulated applying the measured section forces and torques at the rims yielding the motion of all four rims. Then we introduce the specific dynamical tire surrogate model that includes a body that is identified with the rim and

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the definition of a six-dimensional input-quantity called *virtual road profile*. It consist of three translational and three rotational excitation- or input-quantities. Being a six-dimensional quantity, however, it cannot be compared to a real road profile; only the translational inputs may be interpreted in a physical sense.

Based on the motion of the test vehicle's rim, called $q_{rim} \in \mathbb{R}^6$, and the forces and torques that act on the rim and the tire substitute model we derive the virtual road profile in such a way, that a simulation of the tire model would yield a motion of the rim body that equals the rim-motion of the test vehicle in some sense. To achieve this, we use optimal control methods. This is done for all four rims independently. Then, the invariant input load consists of the tire surrogate model and the derived virtual road profile for all four tires. This pair can be transferred to other vehicle variants by connecting the tire substitute model to the vehicle's rim-bodies.

The procedure to derive the virtual profile can be formulated mathematically as an optimal control problem. The tire surrogate model is specific MBS systems, its equations of motions of motion have the form

$$M(q)\ddot{q} = f(F, q, \dot{q}, u), \tag{1}$$

where F represents the section forces and torques, u is the virtual road profile and q are some inner states including the motion of the rim body, $q_{rim} \in \mathbb{R}^6$. Now, suppose that section forces and the rim motion is known from measurement, i.e. $F = F_{REF}$ in eq. (1).To determine u we require that the motion of the rim body of the tire surrogate model equals in a specific sense the rim motion of the test vehicle, which is denoted by q_{REF}: we require that the input u shall minimize the cost functional

$$J[u] := \int_0^T \sum_{j=1}^{6} \big(q_{REF,j}(t) - q_{rim,j}(t)\big)^2 + r \cdot \|u(t)\|^2 dt, \tag{2}$$

subject to equations of motion of the tire surrogate model, eq. (1). r denotes a suitable penalty factor. Note that the input u enters the cost functional not only via the penalty term but also via the (simulated) rim-motion q_{rim}. This is an optimal control problem and can be solved in various ways, see [4, 5]. Optimal control methods in general are discussed in [6, 3].

We emphasize that the input quantity, the virtual road profile, has six dimensions, three input quantities for the translational directions and three for the rotational ones - stressing the fact that we deal with a virtual road profile and not a real profile. For later reference, we introduce the notation

$$u = (u_x, u_y, u_z, u_\alpha, u_\beta, u_\gamma) \in \mathbb{R}^6 \tag{3}$$

for the six-dimensional virtual profile, where u_x, u_y, u_z represent the translational inputs and $u_\alpha, u_\beta, u_\gamma$ the rotational ones.

3 A CASE STUDY

We analyze the previously described approach in a case-study, which is divided into the four following steps.

1. To get section forces and torques we perform a so called *virtual measurement*, i.e., we simulate the drive of a test vehicle model with a complex tire model over a digitalized

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test-track. This provides us with all relevant forces and torques and in the same step with the relevant rim motions. This simulation is called *reference simulation*. In fact, this virtual reference simulation replaces the test drive on a real track, the measurement of the section forces and torques and the simulation performed by applying the measured forces and torques at the rims. However, this replacement does not effect the principle of our approach.

2. Then, we introduce our tire surrogate model and derive the virtual road profile for all four tires following the description in sect. 2.

3. We connect our invariant input load - consisting of the tire surrogate models and the virtual road profiles - to the MBS model of the test vehicle and perform a simulation. We show, that besides numerical errors the same section forces the same motion are reproduced as in the reference simulations. Of course this is a necessary requirement for our proposed approach to be valid.

4. In the last step we analyze the invariance properties of our input loads. To this end we apply the tire surrogate models and the derived virtual road profiles to different vehicle variants. The latter are obtained by changing model parameters such as masses and stiffness- and damping coefficients. For validating purposes we also simulate a drive of the vehicle variants over the same digitalized test-track as in the reference simulation - to get the "true" forces, torques and motions.

The full-vehicle model has been built up in the commercial MBS software package ADAMS, [2]. As complex tire model we used the FTire model, cf. [1].

3.1 Steps 1 and 2: Deriving the virtual profile

Using optimal control methods we derived a virtual road profile, i.e., a six-dimensional time signal, for all four tires. Exemplarily, we plot in fig. (1) the curve $\{(u_x(t), u_z(t)) \mid t \in [0;T]\}$ for the right front side. This curve can be related to the real road profile that was used for the measurement, i.e., the reference simulation in this case; the corresponding curve is plotted, too; they coincide very well.

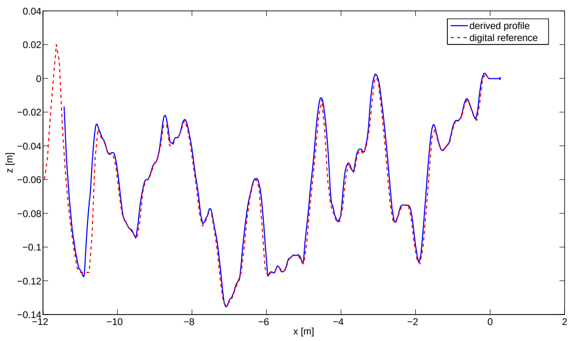

Figure 1: Road profiles

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3.2 Step 3: Verification

As described, the derived profiles together with the tire surrogate models have been coupled to the MBS model of the test-vehicle and simulated. Exemplarily, we consider the left front side. Fig. (2) shows the resulting section forces and torques at the rim when the full-vehicle model is simulated with our tire surrogate model and the derived road profile. The signals are compared to the section forces and torques from the reference simulation. We see that except

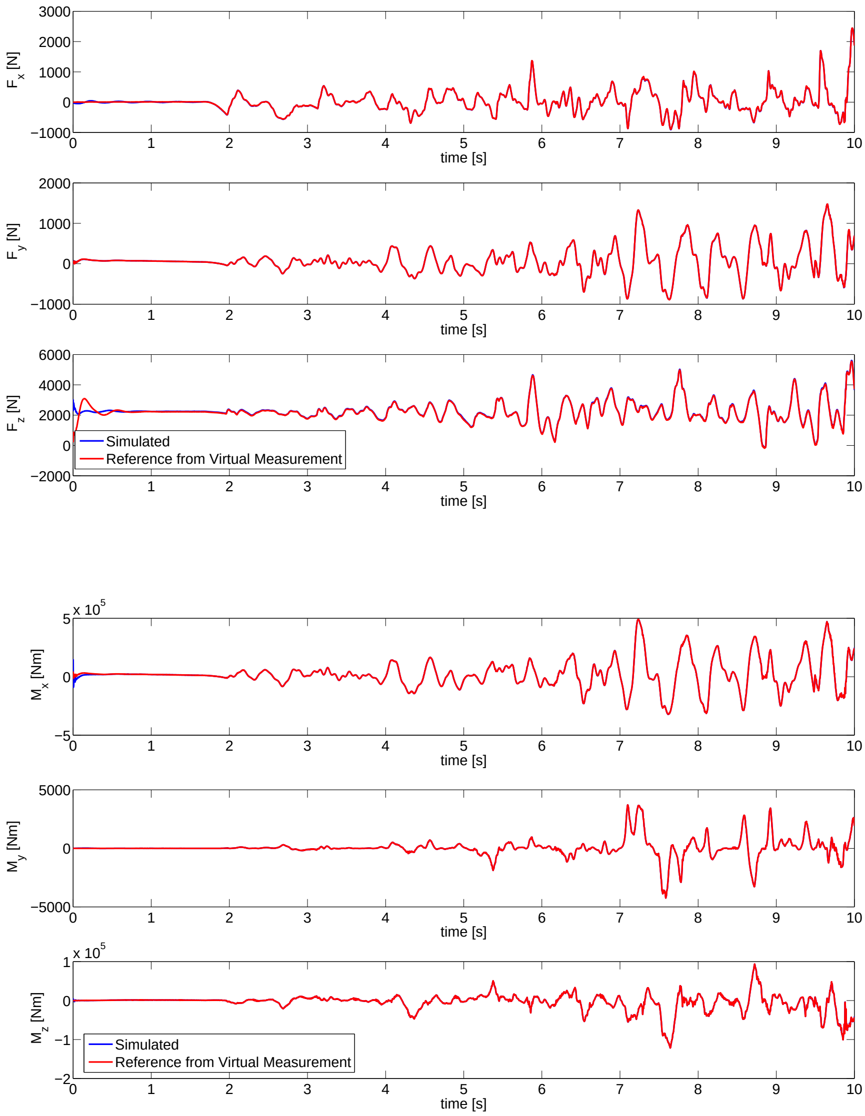

Figure 2: Section forces and torques simulated with reference vehicle model

a short phase at the beginning the curves fit together perfectly on the scale of interest; the necessary verification condition is well satisfied. Other quantities as rim motion, velocity and accelerations are of the same quality.

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3.3 Step 4: Invariance analysis

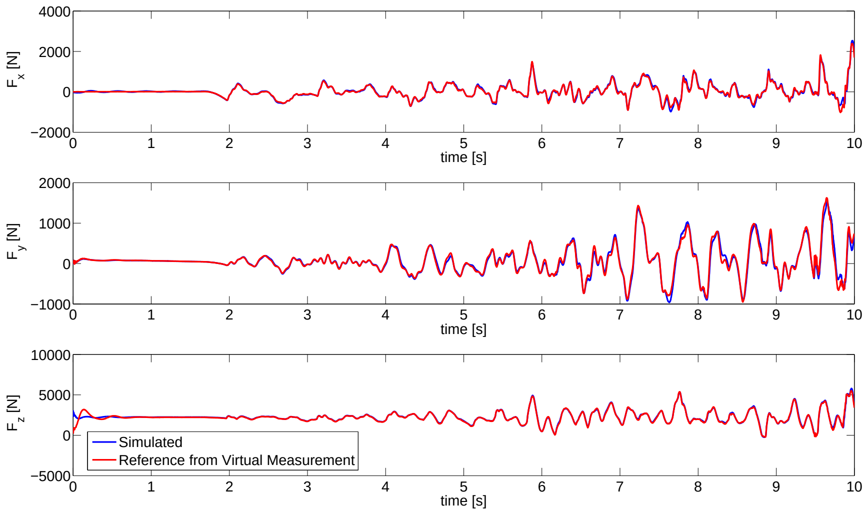
We introduce three vehicle variants by changing some specific model parameters such as stiffness and damping coefficients. The original vehicle model, i.e., the model that has been used in steps 1-3, is referred to as *AutoRef*. The model variants are called *AutoVar1*, *AutoVar2* and *AutoVar3* and their definition with respect to the configuration AutoRef is is given as follows:

AutoVar1: Stiffness-coefficients of the axes' suspensions have been enlarged by 30%.

AutoVar2: Stiffness-coefficients of the axes' suspensions have been reduced by 50% and the mass of the chassis body has been reduced by 100kg.

AutoVar3: Stiffness-coefficients of the axes' suspensions have been enlarged by 50% and the mass of the chassis body has been enlarged by 100kg.

As previously indicated we simulate each of these three variants with the tire surrogate model and the derived profiles. To validate this step, we perform an additional simulation: a further virtual measurement with each of the three variants, the results of both simulation scenarios are compared, cf. fig. (3), (4). Note that this further virtual measurement is *not* available (as real measurement) in real praxis applications; actually, this additional measurement shall be avoided by our approach and we use it only for comparing and validating results. In fig. (3), (4) again the section forces at the rim on the left front-side.



(a) AutoVar1

Figure 3: Section forces and torques simulated with reference vehicle model

The figure shows that the results still fit together very well, however, as expected, the quality is not as good as in step 3, largest deviations are observed in the lateral forces. The model configurations AutoVar1-AutoVar3 cover a certain class of model variants, as they are usual in automotive industry. The results show that our approach gives input data that is invariant w.r.t. to this model class.

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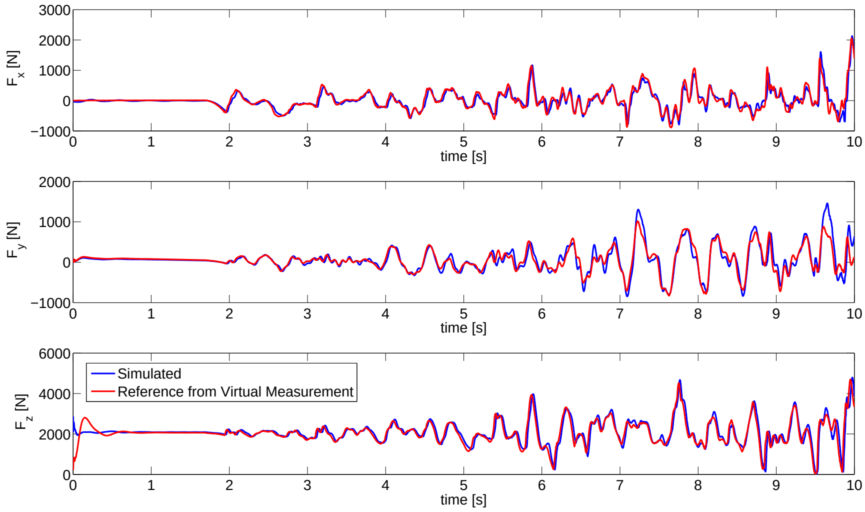
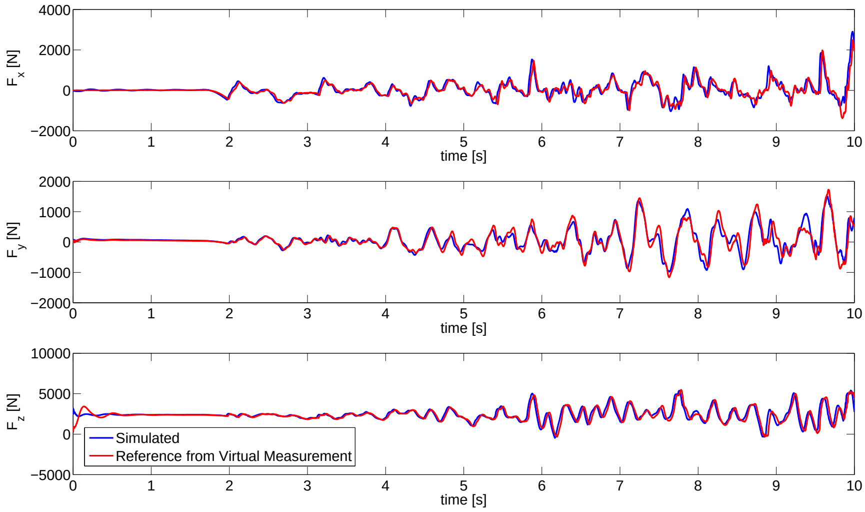


(a) AutoVar2



(b) AutoVar3

Figure 4: Section forces and torques simulated with reference vehicle model

4 CONCLUSIONS

We have presented an approach to derive invariant input data based on measured system-dependent quantities. The input data consist of a tire-surrogate model and a six-dimensional, virtual road profile. The virtual road profile is derived by optimal control methods using the tire surrogate model and measured quantities of a specific reference vehicle, cf. sect. 2 and 3, steps 1-3. In sect. 3 we have shown that this input data is invariant when vehicle model parameters change by up to 50% w.r.t. to the values of reference vehicle.

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The software-routines for deriving the road profile and coupling the tire-surrogate model to a commercial MBS tool as ADAMS have all been developed and implemented at the Fraunhofer-ITWM.

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